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Assessing Worker Exposures During Composite Material Repair: Industrial Hygiene Field Guidance for Bioenvironmental Engineers

Gary N. Carlton, Lieutenant Colonel, USAF, BSC
Ellen C. England, Major, USAF, BSC

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Institute for Environment, Safety and Occupational Health Risk Analysis
Risk Analysis Directorate
Health and Safety Division
2513 Kennedy Circle
Brooks Air Force Base TX 78235-5123

NOTICES

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Robert J. Koogler

ROBERT J. KOOGLER, Lt Col, USAF, MC, SFS
Acting Chief, Health and Safety Division

J Garland

JOHN G. GARLAND III, Col, USAF, BSC
Director, Risk Analysis Directorate

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Gary Carlton, Lt Col
Ellen England, Maj

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IERA/RSHI
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There has been a significant increase in the use of composite materials on Air Force, and their use is expected to increase further as new weapon systems are fielded. Along with the increased use of composites is an increase in composite repair activities in the Air Force. The Structural Maintenance community has expressed concern over inconsistencies in protective equipment requirements from base to base. The Air Force Research Laboratory's Advanced Composites Support Office (ACSO) routinely finds inconsistencies in engineering controls and protective equipment among composite repair facilities throughout the Air Force. As a result of these concerns, the ACSO requested the Industrial Hygiene (IH) Branch of the Institute for ESOH Risk Analysis (IERA) evaluate advanced composite, fiberglass, and aircraft battle damage repair operations in the Air Force and recommend appropriate protective equipment and engineering controls in order to standardize procedures and reduce worker exposures. The IH Branch was also asked to determine whether the ground crew ensemble and protective mask provide adequate protection when performing ABDR operations during training for nuclear, biological, and chemical (NBC) environments. This technical report summarizes our recommended sampling methodology, data interpretation, ventilation requirements, personal protective equipment, and workplace practices for composite material repair.

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ASSESSING WORKER EXPOSURES DURING COMPOSITE MATERIAL REPAIR: INDUSTRIAL HYGIENE FIELD GUIDANCE FOR BIOENVIRONMENTAL ENGINEERS

INTRODUCTION

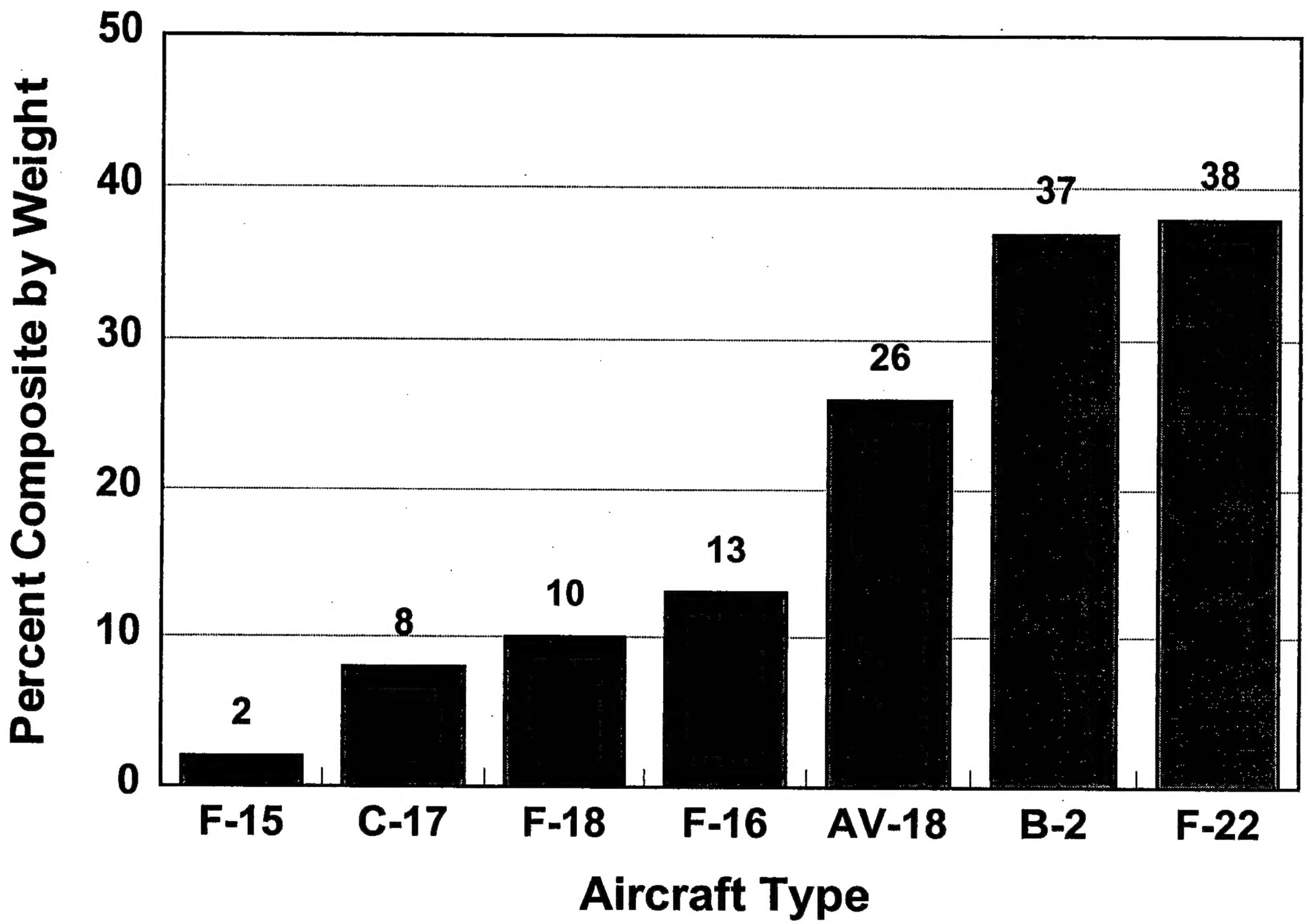
Composite materials are defined as macroscopic combinations of two or more materials. Generally, the term "composites" as used in the Air Force refers to fibers in a polymer matrix. Composites have been around for a very long time; for example, the ancient Egyptians added chopped straw into clay to make bricks stronger. The first application of composites in military aircraft was at the end of World War II, when radomes were fabricated by the wet lay-up of glass fibers woven into a cloth and impregnated with a polyester resin. In the 1960s very strong and stiff ceramic, boron, and carbon fibers became available, and the term "advanced composites" was coined to describe composite materials made from these fibers [1]. There has been a significant increase in the use of composite materials on Air Force aircraft since then, and their use is expected to increase further as new weapon systems are fielded. Figure 1 illustrates the increased use of composites in military aircraft [2].

Along with the increased use of composites is an increase in composite repair activities in the Air Force. The Structural Maintenance community has expressed concern over inconsistencies in protective equipment requirements from base to base. The Air Force Research Laboratory's Advanced Composites Support Office (ACSO), in particular, routinely finds inconsistencies in engineering controls and protective equipment among composite repair facilities throughout the Air Force. As a result of these concerns, the ACSO requested the Industrial Hygiene (IH) Branch of the Institute for ESOH Risk Analysis (IERA) evaluate composite repair operations in the Air Force and recommend appropriate protective equipment and engineering controls in order to standardize procedures and reduce worker exposures. We completed a series of field evaluations at Charleston, Robins, Hill, McClellan, Eglin, Hurlburt AFBs, Cherry Point Naval Aviation Depot (in a joint effort with the Navy Environmental Health Center), and the joint Air Force/Navy Aircraft Structural Maintenance School at Pensacola Naval Air Station. Sampling results from the field evaluations are in Appendices A and B. This technical report summarizes our recommended sampling methodology, data interpretation, ventilation requirements, personal protective equipment, and workplace practices for advanced composite material and fiberglass repair.

In addition to the advanced composite material and fiberglass repair evaluations we performed, the Aircraft Battle Damage Repair (ABDR) Program Management Office requested we evaluate ABDR composite repair operations in the Air Force. Specifically, the IH Branch was asked to recommend appropriate protective equipment and engineering controls to standardize procedures and reduce worker exposures. The IH Branch was also asked to determine whether the ground crew ensemble and protective mask provide adequate protection when performing ABDR operations during training for nuclear, biological, and chemical (NBC) environments. To answer these questions, we completed field evaluations of ABDR operations at Tinker, McClellan, and Hill AFBs. Sampling results from the field evaluations are in Appendix C. The last section of this technical report summarizes our recommended sampling methodology, data interpretation, and personal protective equipment requirements for ABDR composite repair operations.

NOTE: In this technical report, the term "composite repair" is meant to include both advanced composite material (ACM) and fiberglass repair operations.

Figure 1. Composite Material Composition of Selected Military Aircraft



ADVANCED COMPOSITE MATERIAL REPAIR

Description of Composite Materials

Composite materials consist of a reinforcing fiber and a resin. The fibers within composites are the load-bearing elements while the resin molecules fill the voids and transfer the stress from fiber to fiber [3,4]. Composite materials are considered "advanced" composite materials (ACM) if they combine the properties of high strength, high stiffness, low weight, corrosion resistance, and in some cases, special electrical properties. Advanced composites are used in aircraft because they have a higher strength-to-weight ratio than metal components [5]. The most common advanced composite systems found on aircraft include: graphite fiber/epoxy resin; boron fiber/epoxy resin; and aramid fiber/epoxy resin [6] (aramid fibers are manufactured by DuPont under the brand name Kevlar®). The composite material typically consists of a honeycomb core sandwiched between two laminates. This laminate is several layers of resin-impregnated fiber stacked to maximize the material strength [7].

Process Description

Workers perform advanced composite material repair on aircraft parts. These parts are usually removed from the aircraft and repaired in a composite repair or structural maintenance facility, but on occasion the repairs are made while the parts are still on the aircraft. Advanced composite material repair operations vary across the Air Force as Structural Maintenance shops use different tools, techniques, and ventilation systems. However, the repair operations usually consist of the following sequential procedures [8-11]. You can find step-by-step descriptions of these processes in T.O. 1-1-690, *General Advanced Composite Repair Manual* [12].

Damage assessment: Assessment of composite material damage after the part is identified for repair. The part may need repair because of a nick, gouge, or cut in the painted surface, or by a broken piece of composite material missing from the part. Workers perform the assessment by visually inspecting the part, tapping a coin on the part to determine areas of delamination, and marking the area for repair with either masking tape or a marker.

Depainting: Mechanical removal of coatings from the aircraft part surface. Also called scuff sanding, this procedure removes the topcoat and primer to expose the advanced composite material. Workers depaint the parts with either a pneumatic rotary right angle grinder, a straight grinder, a rotary dual action sander, or a random orbital sander. Mechanical abrasion results in the generation of inhalable particulates and possible chromate exposures if the primer coating contains strontium, zinc, or lead chromate.

Clean wiping: Removal of dust, dirt, and oil from the depainted surfaces. After depainting, residual dust is present on the part. After removing the majority of the dust with compressed air or brushing, the worker wipes a solvent on the part with a clean rag. Several different solvents are available, including methyl ethyl ketone, acetone, or isopropyl alcohol; the most common solvent is isopropyl alcohol. The procedure is normally less than ten minutes in length, but the time devoted to clean wiping depends on the size of the surface area the worker is cleaning. Exposures result from solvent vaporization, but are usually limited because of the brevity of the operation.

Damage Removal/Scarfing: Mechanical removal of damaged advanced composite material and chamfering of the laminate. Also called grinding, this procedure removes small quantities of damaged composite material so the workers can apply a flush patch. Proper scarfing exposes each layer of the laminate; the layers appear as concentric circles around the center of the damaged area. Workers usually

scarf with either a pneumatic rotary straight or right angle grinder, such as the Dotco®. One, two, and three inch grinding discs may be attached to the grinders. The most common grit size used for scarfing is 80, although workers may use different other grits depending upon the advanced composite material being abraded. Inhalable and respirable particulate exposures may occur; a small number of fibers may also be generated.

Core repair: Rebuilding or filling in damaged areas of the honeycomb core material. If the core material is damaged in addition to the overlaying laminate, the worker may need to fill-in the existing core with an epoxy-based compound to improve its strength. Occasionally, the core material is damaged beyond repair, and must be completely replaced. The worker replaces the core material by cutting a section from the damaged core and installing a new section of honeycomb material using an epoxy potting compound. Worker skin exposures to unreacted epoxy and amine compounds may occur while the potting compound is mixed and applied.

Lay-up: Designing, cutting, and stacking of advanced composite material cloth to form a laminate or patch. There are two types of lay-up operations: wet lay-up and pre-preg lay-up. In wet lay-up operations, a resin, usually epoxy-based, is mixed with a hardener, usually amine-based. This mixture is applied to an advanced composite cloth material, which is cut and stacked to form a laminate. In pre-preg lay-up, the advanced composite material cloth is already pre-impregnated with a resin and hardener. The pre-preg material is cut and stacked to form a laminate, then attached to the scarfed area using a film adhesive. The resin systems present a skin contact hazard to personnel from the uncured epoxy and amine groups.

Curing: Solidifying the laminate by placing it under heat and pressure. Workers place the laminate underneath a vacuum bag to ensure a uniform pressure is applied. The laminate is then cured in an autoclave, beneath a heat blanket, or under heat lamps. There is little potential for exposures to personnel during curing because of the vacuum bagging technique.

Air Sampling Methodology

During advanced composite repair operations, workers can be exposed to particulates (fibrous and non-fibrous), chromates, solvent vapors, and uncured epoxy and amine groups. Table 1 summarizes our sampling recommendations.

Particulates: Particulates generated during advanced composite repair procedures vary in size and form a particulate mass distribution. There are four types of particulate distributions of interest to the industrial hygienist: the total aerosol mass; the inhalable particulate mass; the thoracic particulate mass; and the respirable particulate mass [13]. These distributions are based upon the aspiration and deposition characteristics of the human respiratory tract. The primary size distributions of interest during advanced composite repair are the inhalable and respirable mass distribution. The inhalable mass is the portion of the total aerosol mass the worker actually breathes into the respiratory tract, while the respirable mass is that portion of the total aerosol that ends up in the gas-exchange region of the lungs.

Inhalable Particulates (Non-Fibrous): The most well known and readily available inhalable mass sampler is the Institute of Occupational Medicine (IOM) sampler, marketed through SKC®. It uses a 25-mm filter placed inside a removable cassette with a 15-mm inlet opening. The cassette and filter are weighed together before and after sampling. Particulates collected both on the filter and on the walls of the cassette represent the inhalable mass fraction [14]. There are two problems with the IOM that may not make it practical for your use. First, to weigh the cassette/filter combination, you need a scale that has at least 0.001 mg sensitivity but can handle a tare weight of approximately 25 mg, the weight of the

Table 1. Recommended Sampling Methodology - Advanced Composite Material Repair

Operation	Substance	Sampling Method	Sampling Media	Sample Flow Rate (lpm)
Depainting	Inhalable Particulate (non-fibrous)	NIOSH 0500	5-µm PVC filter, 37-mm cassette with 15-mm hole drilled in cap **or** IOM sampler	2.0
	Chromium (hexavalent)	NIOSH 7300	0.8-µm MCE filter, 37-mm cassette with 15-mm hole drilled in cap	2.0
Clean Wiping	Acetone	NIOSH 1300	coconut shell charcoal tube	0.2
	Isopropyl Alcohol	NIOSH 1400	coconut shell charcoal tube	0.2
	Methyl Ethyl Ketone	NIOSH 2500	beaded carbon tube (Anasorb 747)	0.2
Scarfing	Inhalable Particulate (non-fibrous)	NIOSH 0500	5-µm PVC filter, 37-mm cassette with 15-mm hole drilled in cap **or** IOM sampler	2.0
	Respirable Particulate (non-fibrous)	NIOSH 0600	5-µm PVC filter, 37-mm cassette with respirable cyclone	1.7 (nylon) 2.5 (aluminum)
	Fibers	NIOSH 7400	0.8-µm MCE filter, 25-mm cassette with conductive cowl	2.0

cassette [14]. These scales exist, but are very expensive. Second, the IOM is relatively expensive and cannot be reused if wish to analyze your samples for metals such as chromates. As an alternative, we recommend you use a 37-mm cassette with a 15-mm hole drilled in the cassette cap to simulate the characteristics of the IOM sampler. Sampling depainting and scarfing operations in closed-face mode will seriously underestimate worker exposures. To reduce bias from sampler orientation, use a cassette holder designed to keep the cassette face parallel to the worker's body (see Figure 2) [15]. Use 5.0-μm PVC filters as the sampling media. Sample at 2.0 liters per minute (lpm). Analyze the filters per NIOSH Method 0500, which requires pre- and post-weighing filters with a 0.001 mg sensitivity scale [16]. If you don't have such a scale available, use match-weighted filters and submit for analysis.

Respirable Particulates (Non-fibrous): To sample for respirable dust use a respirable cyclone. The cyclone separates the larger particles from the aerosol size distribution, collecting the respirable mass on a filter. The most common cyclones in use are the MSA® nylon cyclone and the SKC® aluminum cyclone. These two cyclones are slightly different in design and require different flow rates to operate properly: 1.7 lpm for the MSA nylon cyclone and 2.5 lpm for the SKC aluminum cyclone [17]. Use a 5-μm PVC filter mounted in a 37-mm cassette attached to the cyclone. Analyze according to NIOSH Method 0600 [18], which is similar to Method 0500 used for inhalable mass sampling, requiring pre- and post-weighing of filters or, in the absence of a scale, match-weighted filters.

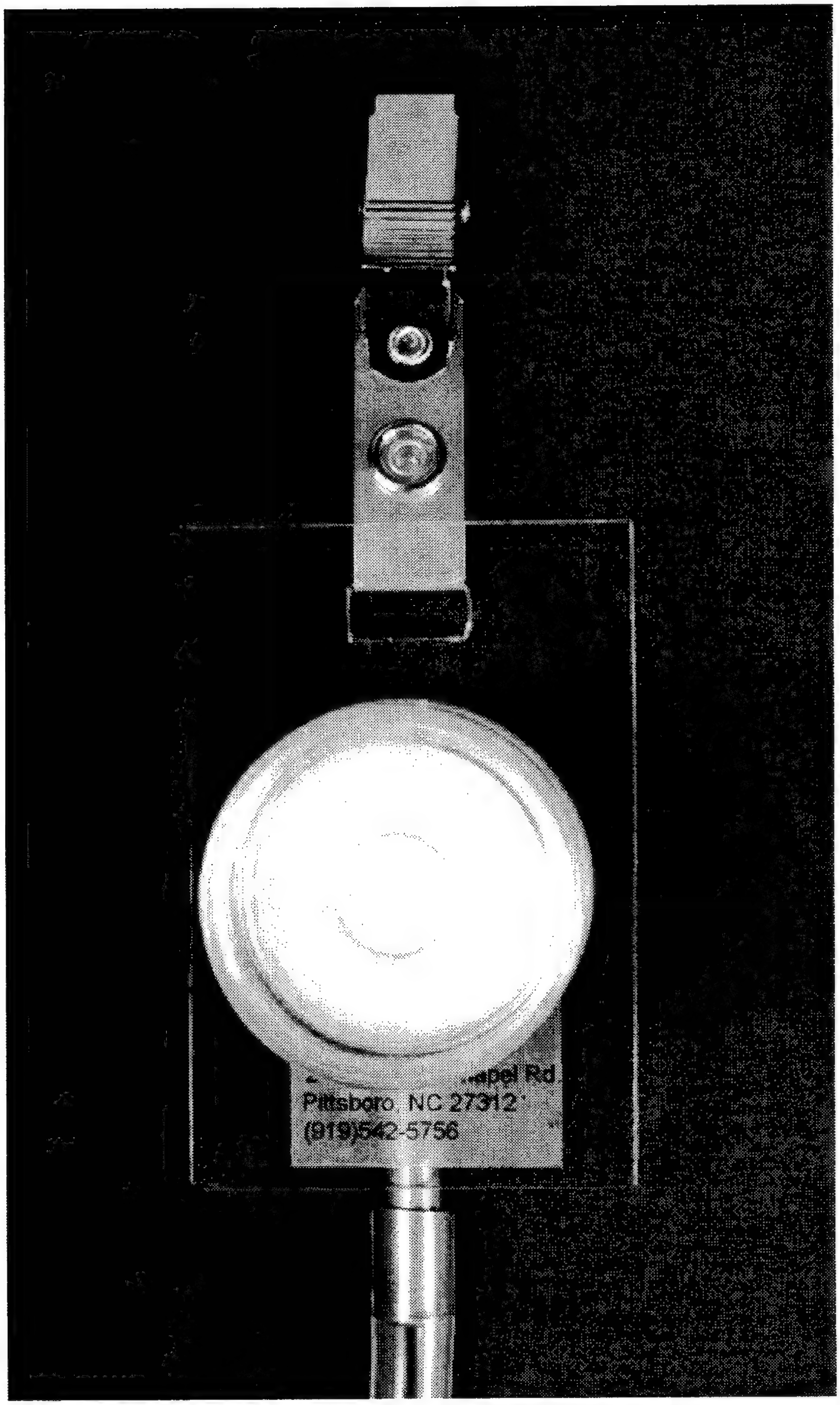
Fibers: Sample for fibers with NIOSH Method 7400, which is the same method you use to sample for asbestos [19]. Use 0.8-μm MCE filters mounted in a 25-mm cassette with an anti-static cowl (the cowl causes spurious fibers, such as from clothing, to adhere to the cassette, preventing them from depositing on the filter). Sample at 2.0 lpm. On the sampling form, request NIOSH 7400 and specify the type of fiber you suspect is present based on the type of composite material in the aircraft part, i.e., graphite, boron, or aramid. Make sure the analysis is done under the alternate counting rules for non-asbestos fibers (also called the "B" counting rules).

Hexavalent Chromium: Use 0.8 μm mixed-cellulose ester (MCE) filters placed in a 37-mm cassette. Sample at 2.0 lpm. As with inhalable particulate sampling, drill a 15-mm hole in the cassette cap to collect the inhalable mass fraction. The analytical method (NIOSH 7300) does not analyze specifically for chromates ($[CrO_4]^{-2}$), but for the total amount of chromium (Cr) [20]. Therefore, make the assumption that all Cr reported by the lab is present as chromate. Realize that some of the Cr found by the lab may not be tied-up as chromate, but may be either Cr III compounds or Cr VI compounds other than chromates. Request "chromium" on the sampling form. Request the lab report the total mass collected. A more complete discussion of sampling for chromates and interpretation of the results is in the IH Branch Field Guide, *Analysis of Chromate Sampling Data* [21]. This field guide is available on the IH Branch web site.

Solvent Vapors: To sample for solvents during clean wiping, use NIOSH Method 1300 for acetone and NIOSH 1400 for isopropyl alcohol. Both of these methods use coconut shell charcoal tubes as the sampling media [22,23]. To sample for methyl ethyl ketone, use NIOSH 2500 [24]. This method uses Anasorb® 747 sorbent tubes. Anasorb is a trade name for a type of sorbent tube marketed by SKC®. It is a beaded synthetic carbon of low ash content.

Unreacted Epoxy/Amine Groups: No air sampling is required during core repair or lay-up operations as the resins and hardeners contain epoxy resins and aliphatic amines that are non-volatile at the normal room temperatures the workers use them [25]. The resins and amines are volatilized during curing, but the vapors are contained by the vacuum bagging technique, which minimizes worker exposures. Sampling by the IH Branch has confirmed that exposures to resins and amines during these operations are below detectable analytical limits [8,9].

Figure 2. Three-Piece Cassette With Modified Cap and Holder



Data Evaluation

Process Timelines: Sample each composite repair procedure separately. Sample as many workers involved in each task as possible. Make sure to record a timeline during each procedure, specifically the time the workers actually perform the procedure (task length). The task length is not necessarily the time the sampling pumps were turned on and off, since workers tend to take breaks or do other work during the procedures.

Exposure Calculation: Calculate both the task exposure and the 8-hr time-weighted average (TWA) exposure. The task exposure is the average concentration over the length of the task, and is useful for determining effectiveness of engineering controls and respiratory protection. For example, engineering controls that keep task exposures below the 8-hr TWA exposure limit will protect the worker even if an operation is performed for an entire eight-hour workday. Use the following equations to calculate the exposures:

$$\text{Task Exposure} = \frac{(\text{mg contaminant})(10^3\ \text{lit/m}^3)}{(\text{sampling rate [lit/min]})(\text{task length [min]})}$$

$$8\text{-hr TWA} = (\text{Task Exposure})\left(\frac{\text{task length [min]}}{480\ \text{min}}\right)$$

Comparison to Exposure Standards: The Air Force OELs and OSHA PELs for most of the substances you'll encounter during advanced composite repair are shown in Table 2 [13,26]. If you encounter a type of composite that does not have an established exposure limit, that does not preclude air sampling. Air sampling is needed to document exposures in case an exposure standard is adopted in the future and to determine the effectiveness of engineering controls. As mentioned above, the analytical method for chromates (NIOSH 7300) cannot differentiate among the various types of chromium compounds, so assume all the chromium reported by the lab is chromate. Compare the 8-hr TWA to the OEL for the chromate you sampled for (use 0.0005 mg/m^3, the current AF OEL for strontium chromate, if you don't know what type of chromate the workers were exposed to). Because the OSHA PEL for chromates is a ceiling limit, in theory this is a limit that should never be instantaneously exceeded during the procedures. As a practical matter, however, it's difficult to measure instantaneous levels of chromates, so compare the task exposure for each procedure to the PEL, the task exposure being the closest approximation to the instantaneous exposure. A chromate task exposure exceeding the PEL indicates non-compliance.

Table 2. Exposure Limits for Substances Encountered During Advanced Composite Material Repair

Substance	Composite Material	Air Force OEL (mg/m^3)		OSHA PEL (mg/m^3)
		15-min STEL	8-hr TWA	8-hr TWA
Inhalable Particulate (non-fibrous)	Graphite	--	--	15.0
	Boron	--	10.0	15.0
	Aramid	--	10.0	15.0
Respirable Particulate (non-fibrous)	Graphite	--	2.0	5.0
	Boron	--	3.0	5.0
	Aramid	--	3.0	5.0
Fibers	Graphite	--	1.0[a]	--
	Boron	--	1.0[a]	--
	Aramid	--	1.0[a]	--
Chromium (hexavalent)	--	--	0.0005[b]	0.05[c]
Acetone	--	1780	1190	2400
Isopropyl Alcohol	--	1230	983	980
Methyl Ethyl Ketone	--	300	200	590

[a]Units f/cc; by analogy to Synthetic Vitreous Fibers

[b]Assumes strontium chromate; use appropriate standard for other chromates

[c]Ceiling limit

FIBERGLASS REPAIR

Description of Fiberglass Material

Fiberglass is a composite material consisting of a reinforcing glass fiber and a resin. The fibers are the load-bearing elements while the resin fills the voids and transfers the stress from fiber to fiber [3,4]. Fiberglass materials are used in aircraft where material strength and low material weight are required. The most common fiberglass composite system found on aircraft uses a continuous filament glass fiber (referred to as E-glass) woven into a material cloth and held together with an epoxy resin system [5]. Other glass fibers with different compositions that are found to a lesser degree on aircraft are S-glass and quartz. The fiberglass aircraft part may consist of a honeycomb core sandwiched between two laminates or a solid laminate of resin-impregnated fibers stacked to maximize material strength. Typical aircraft locations for fiberglass panels are electrical transparency applications (radomes, antennas, dielectric edges), wear strips, access panels, and other lightly loaded structures. Interior panels and cockpit panels are often fiberglass composites.

Process Description

Workers perform fiberglass repair operations on aircraft parts. These parts are usually removed from the aircraft and repaired in a composite repair or structural maintenance facility, but on occasion the repairs are made while the parts are still on the aircraft. Fiberglass repair operations vary across the Air Force as Structural Maintenance shops use different tools, techniques, and ventilation systems. However, the repair operations usually consist of the following sequential procedures [27-31]. You can find step-by-step descriptions of these processes in T.O. 1-1-690, *General Advanced Composite Repair Manual* [12].

Damage assessment: Assessment of fiberglass material damage after the part is identified for repair. The part may be identified for repair because of a nick, gouge, or cut in the painted surface or by a broken or missing piece of fiberglass material. Workers perform the assessment by visually inspecting the part and marking the area for repair using either a marker or masking tape. Instrumented inspection techniques such as x-ray, ultrasonics, shearography, or thermography are also used.

Sanding/grinding: Mechanical removal of coatings and damaged fiberglass material from the surface of the aircraft part. This procedure removes the topcoat, primer, and a portion of the damaged fiberglass. Some workers may initially remove the topcoat and primer before mechanically abrading the fiberglass to get a better look at the damage. Most workers, however, abrade both the coatings and fiberglass material at the same time. Workers may sand/grind using a pneumatic rotary right angle grinder such as the Dotco®, a straight grinder, or a rotary dual-action orbital sander. One, two, and three inch grinding discs may be attached to the grinders, while five inch is the most common sanding disc size. The most common grit sizes used during sanding are 80 and 120, although workers may use different sizes of grits. Sanding through the topcoat into the primer releases inhalable and respirable particulates, including those that contain chromates. As the fiberglass composite material is sanded, inhalable and respirable particulates are generated, along with a very minimal number of glass fibers (referred to as synthetic vitreous fibers) [32,33]. The fiberglass particulates are composed of several different metallic oxides present within the original glass fiber, including silicon, calcium, boron, and aluminum [34]. The silicon oxide (SiO_2, also called silica) is in the amorphous form in E- and S-glass, and therefore is a nuisance dust, but there may be a small quantity of crystalline quartz interspersed. The silicon oxide in quartz glass is also the amorphous form even though it's called "quartz" glass [35].

Clean wiping: Removal of dust, dirt, and oil from the sanded surface. After sanding/grinding, residual dust is present on the part. Workers commonly remove the majority of the dust with compressed air or brushing, then wipe a solvent on the part with a clean rag. Several different solvents are available, including methyl ethyl ketone, acetone, or isopropyl alcohol; the most commonly used is isopropyl alcohol. The procedure is normally less than ten minutes in length, but the time devoted to clean wiping depends on the size of the surface area the worker is cleaning. Worker exposures result from the vaporization of the solvent applied to the part, but are usually limited because of the brevity of the operation.

Core repair: Rebuilding or filling in damaged areas of the honeycomb core material. If the core material is damaged in addition to the overlaying laminate, the worker may need to fill-in the existing core with an epoxy-based compound to improve its strength. Occasionally, the core material is damaged beyond repair and must be completely replaced. The worker replaces the core material by cutting a section from the damaged core and installing a new section of honeycomb material using an epoxy potting compound. Worker skin exposures to unreacted epoxy and amine compounds may occur while the potting compound is mixed and applied.

Wet Lay-up: Cutting and stacking of fiberglass cloth to form a laminate or patch. A resin, usually epoxy-based, is mixed with a hardener, usually amine-based. Workers pour this mixture on the fiberglass cloth then spread the mixture with a spatula. The fiberglass cloth material is then cut and stacked to form a laminate. A vacuum bag is put into place over the laminate. The resin systems present a skin contact hazard to personnel from uncured epoxy and amine groups.

Curing: Solidifying the laminate by placing it under heat and pressure. Workers place the laminate under a vacuum bag to ensure uniform pressure is applied. The laminate is then cured on the aircraft part by the heat generated from heat lamps. There is little potential for exposures to personnel during curing because of the vacuum bagging technique.

Air Sampling Methodology

During fiberglass repair operations, workers can be exposed to non-fibrous particulates (consisting of metallic oxides), glass fibers, chromates, crystalline silica (quartz), solvent vapors, and uncured epoxy and amine groups. Table 3 summarizes our sampling recommendations.

Non-Fibrous Particulates: Particulates generated during fiberglass repair procedures vary in size and form a particulate mass distribution. There are four types of particulate distributions of interest to the industrial hygienist: the total aerosol mass; the inhalable particulate mass; the thoracic particulate mass; and the respirable particulate mass [13]. These distributions are based upon the aspiration and deposition characteristics of the human respiratory tract. The primary size distributions of interest during fiberglass repair are the inhalable and respirable mass distribution. The inhalable mass is the portion of the total aerosol mass the worker actually breathes into the respiratory tract, while the respirable mass is that portion of the total aerosol that ends up in the gas-exchange region of the lungs.

Inhalable Particulates: The most well known and readily available inhalable mass sampler is the Institute of Occupational Medicine (IOM) sampler, marketed through SKC®. It uses a 25-mm filter placed inside a removable cassette with a 15-mm inlet opening. The cassette and filter are weighed together before and after sampling. Particulates collected both on the filter and on the walls of the cassette represent the inhalable mass fraction [14]. There are two problems with the IOM that may not make it practical for your use. First, to weigh the cassette/filter combination, you need a scale that has at least 0.001 mg sensitivity but can handle a tare weight of approximately 25 mg, the weight of the cassette

Table 3. Recommended Sampling Methodology - Fiberglass Repair

Operation	Substance	Sampling Method	Sampling Media	Sample Flow Rate (lpm)
Sanding/Grinding	Inhalable Particulate (non-fibrous)	NIOSH 0500	5-µm PVC filter, 37-mm cassette with 15-mm hole drilled in cap **or** IOM sampler	2.0
	Chromium (hexavalent)	NIOSH 7300	0.8-µm MCE filter, 37-mm cassette with 15-mm hole drilled in cap	2.0
	Respirable Particulate (non-fibrous)	NIOSH 0600	5-µm PVC filter, 37-mm cassette with respirable cyclone	1.7 (nylon) 2.5 (aluminum)
	Crystalline Silica (quartz)	NIOSH 7602	5-µm PVC filter, 37-mm cassette with respirable cyclone	1.7 (nylon) 2.5 (aluminum)
	Synthetic Vitreous Fibers	NIOSH 7400	0.8-µm MCE filter, 25-mm cassette with conductive cowl	2.0
Clean Wiping	Acetone	NIOSH 1300	coconut shell charcoal tube	0.2
	Isopropyl Alcohol	NIOSH 1400	coconut shell charcoal tube	0.2
	Methyl Ethyl Ketone	NIOSH 2500	beaded carbon tube (Anasorb 747)	0.2

[14]. These scales exist, but are very expensive. Second, the IOM is relatively expensive and cannot be reused if wish to analyze your samples for metals such as chromates. As an alternative, we recommend you use a 37-mm cassette with a 15-mm hole drilled in the cassette cap to simulate the characteristics of the IOM sampler. Sampling sanding/grinding operations in closed-face mode will seriously underestimate worker exposures. To reduce bias from sampler orientation, use a cassette holder designed to keep the cassette face parallel to the worker's body (see Figure 2) [15]. Use 5.0-µm PVC filters as the sampling media. Sample at 2.0 liters per minute (lpm). Analyze the filters per NIOSH Method 0500, which requires pre- and post-weighing filters with a 0.001 mg sensitivity scale [16]. If you don't have such a scale available, use match-weighted filters and submit for analysis.

Respirable Particulates: To sample for respirable dust use a respirable cyclone. The cyclone separates the larger particles from the aerosol size distribution, collecting the respirable mass on a filter. The most common cyclones in use are the MSA® nylon cyclone and the SKC® aluminum cyclone. These two cyclones are slightly different in design and require different flow rates to operate properly: 1.7 lpm for the MSA nylon cyclone and 2.5 lpm for the SKC aluminum cyclone [17]. Use a 5-µm PVC filter mounted in a 37-mm cassette attached to the cyclone. Analyze according to NIOSH Method 0600 [18], which is similar to Method 0500 for inhalable mass sampling, requiring pre- and post-weighing of filters or, in the absence of a scale, match-weighted filters.

Synthetic Vitreous Fibers: Sample for glass fibers with NIOSH Method 7400, which is the same method you use to sample for asbestos [19]. Use 0.8-µm MCE filters mounted in a 25-mm cassette with an anti-static cowl (the cowl causes spurious fibers, such as from clothing, to adhere to the cassette, preventing them from depositing on the filter). Sample at 2.0 lpm. On the sampling form, request NIOSH 7400 and specify fiberglass. Make sure the analysis is done under the alternate counting rules for non-asbestos fibers (also called the "B" counting rules).

Hexavalent Chromium: Use 0.8 µm mixed-cellulose ester (MCE) filters placed in a 37-mm cassette. Sample at 2.0 lpm. As with inhalable particulate sampling, drill a 15-mm hole in the cassette cap to collect the inhalable mass fraction. The analytical method (NIOSH 7300) does not analyze specifically for chromates ($[CrO_4]^{-2}$), but for the total amount of chromium (Cr) [20]. Therefore, make the assumption that all Cr reported by the lab is present as chromate. Realize that some of the Cr found by the lab may not be tied-up as chromate, but may be either Cr III compounds or Cr VI compounds other than chromates. Request "chromium" on the sampling form. Request the lab report the total mass collected. A more complete discussion of sampling for chromates and interpretation of the results is in the IH Branch Field Guide, *Analysis of Chromate Sampling Data* [21]. This field guide is available on the IH Branch web site.

Crystalline Silica (Quartz): As mentioned above, crystalline silica in fiberglass is present in the form of quartz, so you need to sample for it differently than for the other metallic oxides. To sample for crystalline silica during sanding/grinding, use NIOSH Method 7602. Use 5-µm PVC filters mounted in a 37-mm cassette attached to a respirable cyclone [36].

Solvent Vapors: To sample for solvents during clean wiping, use NIOSH Method 1300 for acetone and NIOSH 1400 for isopropyl alcohol. Both of these methods use coconut shell charcoal tubes as the sampling media [22,23]. To sample for methyl ethyl ketone, use NIOSH 2500 [24]. This method uses Anasorb® 747 sorbent tubes. Anasorb is a trade name for a type of sorbent tube marketed by SKC®. It is a beaded synthetic carbon of low ash content.

Unreacted Epoxy/Amine Groups: No air sampling is required during core repair or wet lay-up operations as the resins and hardeners contain epoxy resins and aliphatic amines that are non-volatile at

the normal room temperatures the workers use them [25]. The resins and amines are volatilized during curing, but the vapors are contained by the vacuum bagging technique, which minimizes worker exposures. Sampling by the IH Branch has confirmed that exposures to resins and amines during these operations are below detectable analytical limits [28,31].

Data Evaluation

Process Timelines: Sample each fiberglass repair procedure separately. Sample as many workers involved in each task as possible. Make sure to record a timeline during each procedure, specifically the time the workers actually perform the procedure (task length). The task length is not necessarily the time the sampling pumps were turned on and off, since workers tend to take breaks or do other work during the procedures.

Exposure Calculations: Calculate both the task exposure and the 8-hr time-weighted average (TWA) exposure. The task exposure is the average concentration over the length of the task, and is useful for determining effectiveness of engineering controls and respiratory protection. For example, engineering controls that keep task exposures below the 8-hr TWA exposure limit will protect the worker even if an operation is performed for an entire eight-hour workday. Use the following equations to calculate the exposures:

$$\text{Task Exposure} = \frac{(\text{mg contaminant})(10^3\ \text{lit/m}^3)}{(\text{sampling rate [lit/min]})(\text{task length [min]})}$$

$$8\text{-hr TWA} = (\text{Task Exposure})\left(\frac{\text{task length [min]}}{480\,\text{min}}\right)$$

The particulates generated during fiberglass sanding are composed of several metallic oxides that are present within the original glass fiber. Typical metallic oxide content of the fiberglass used in aircraft components is shown in Table 4 [34]. Note: the weight fractions of individual components in Table 5 do not add up to 1.0 as fiber composition may vary. To evaluate exposures to these constituents, multiply the total inhalable particulate exposure (either task or 8-hr TWA) by the weight fractions of the individual

Table 4. Composition of Fiberglass

Substance	Maximum Weight Fraction		
	E-Glass	S-Glass	Quartz
Aluminum oxide	0.16	0.26	--
Boron oxide	0.10	--	--
Calcium oxide	0.25	--	--
Iron oxide	0.008	--	--
Magnesium oxide	0.05	0.11	--
Potassium oxide	0.02	--	--
Silicon dioxide	0.56	0.66	1.0
Sodium oxide	0.18	--	--
Titanium oxide	0.015	--	--

metallic oxides (MeO) in the glass substrate:

$$\text{MeO Exposure (Task)} = (\text{Inhalable Exposure[Task]})(\text{Weight fraction of MeO})$$

$$\text{MeO Exposure (8 - hr TWA)} = (\text{Inhalable Exposure[8 - hr TWA]})(\text{Weight fraction of MeO})$$

Comparison to Exposure Standards: The Air Force OELs and OSHA PELs for most of the substances you'll encounter during fiberglass repair are shown in Table 5 [13,26]. Of the metal oxides, only aluminum, boron, calcium, iron, and titanium oxides have established exposure limits; the other metal oxides, including non-crystalline (amorphous) silicon dioxide, are nuisance particulates. As mentioned above, the analytical method for chromates (NIOSH 7300) cannot differentiate among the various types of chromium compounds, so assume all the chromium reported by the lab is chromate. Compare the 8-hr TWA to the OEL for the chromate you sampled for (use 0.0005 mg/m^3, the current AF OEL for strontium chromate, if you don't know what type of chromate the workers were exposed to). Because the OSHA PEL for chromates is a ceiling limit, in theory this is a limit that should never be instantaneously exceeded during the procedures. As a practical matter, however, it's difficult to measure instantaneous levels of chromates, so compare the task exposure for each procedure to the PEL, the task exposure being the closest approximation to the instantaneous exposure. A chromate task exposure exceeding the PEL indicates non-compliance.

Table 5. Exposure Limits for Substances Encountered During Fiberglass Repair

Substance	Air Force OEL (mg/m^3)		OSHA PEL (mg/m^3)
	15-min STEL	8-hr TWA	8-hr TWA
Inhalable Particulate (non-fibrous)			
Total	--	10.0	15.0
Aluminum Oxide	--	10.0	--
Boron Oxide	--	10.0	15.0
Calcium Oxide	--	2.0	5.0
Iron Oxide	--	2.1	--
Titanium Oxide	--	10.0	15.0
Respirable Particulate (non-fibrous)	--	3.0	5.0
Chromium (hexavalent)	--	0.0005[a]	0.05[b]
Synthetic Vitreous Fibers			
Continuous Filament Glass Fibers	--	1.0[c]	--
Crystalline Silica			
Quartz	--	0.1	Out of date
Wipe Solvents			
Acetone	1780	1190	2400
Isopropyl Alcohol	1230	983	980
Methyl Ethyl Ketone	300	200	590

[a]Assumes strontium chromate; use appropriate standard for other chromates

[b]Ceiling limit

[c]Units f/cc

VENTILATION OF COMPOSITE REPAIR OPERATIONS

Advanced composite material and fiberglass repairs generally are accomplished with some form of ventilation. Ventilation systems you may encounter at your base include crossflow sanding booths, hand-held vacuum hoses, downdraft tables, moveable exhaust hoods with flexible ducting, and ventilated pneumatic tools (also referred to as low volume-high velocity exhaust systems). The primary purpose of the ventilation system is to collect particulates generated during depainting/scarfing and sanding/grinding procedures [37]. Of these five types of systems, our surveys indicate that moveable exhaust hoods and ventilated tools used in conjunction with crossdraft booths provide the best control of particulates generated during in-shop composite repair operations. For repairs on parts installed on aircraft, ventilated tools are the most appropriate choice to capture graphite and metallic dusts and prevent them from contaminating other aircraft components.

Ventilation Systems

Crossflow Sanding Booths: Fiberglass repairs typically take place in crossflow sanding booths because most aircraft fiberglass parts are relatively large. Most crossflow sanding booths in the Air Force are essentially paint booths in which sanding/grinding is done. There are, however, commercially available sanding booths designed specifically for composite repair; one example is the Torit® Power Module. They are not as effective at controlling particulates as downdraft tables, hand-held vacuum hoses, moveable exhaust hoods, and ventilated tools, which capture particulates at the source of generation. Workers frequently position themselves between the part being sanded/scarfed and the exhaust location, causing contaminants to pass through their breathing zone and increasing their exposures. Sanding booths can be effective in reducing exposures, though, if used in conjunction with some of the other systems listed below. There are no current guidelines in the industrial hygiene literature on effective ventilation rates for crossflow sanding booths.

Hand-Held Vacuum Hoses: Workers occasionally hold a vacuum hose near the part being scarfed to collect particulates generated. The hose is typically attached to a vacuum equipped with a high-efficiency particulate air (HEPA) filter. This system is more effective than a crossflow sanding booth because it collects particulates closer to the point of generation, but can cause significant fatigue for the workers since they are holding the hose in one hand and the pneumatic tool in the other. Holding the hose with the free hand also results in the workers' breathing zones being physically closer to the point of contaminant generation, increasing exposures. If your base uses hand-held vacuum hoses, they should have air flows similar to those for moveable exhaust hoods.

Downdraft Tables: Downdraft tables have grilles on the table surface through which particulates are drawn. They usually have back and side shields to enclose the operation as much as possible. Air is drawn by a fan through a filter bank and exhausted either into the same room the booth is in or to the outside of the building, depending on the design. Positioning of the part on the table can influence the ability to collect particulates depending on the design of the table, because air velocities can vary widely across the table surface. Measure air velocities across the surface of the downdraft table. Take sufficient measurements to estimate the average flow. An air flow of 150-250 cubic feet per minute (cfm) per square foot of table surface area is recommended [37].

Moveable Exhaust Hoods: Moveable exhaust hoods generally have flexible exhaust ducts connected to a relatively small exhaust hood. A hinged arm may support the hood to allow positioning of the hood

near the source of dust generation. Ensure the hood is placed within a few inches of the work surface and positioned toward the direction particulates are being thrown. Measure air velocities across the face of the exhaust hood; take sufficient measurements to estimate the average flow. A minimum volumetric air flow of 400 cfm with a minimum duct velocity of 4000 feet per minute (fpm) is recommended [37].

Ventilated Pneumatic Tools: Ventilated sanders and grinders typically have a number of holes located in the rotary disc through which particulates are drawn. The tool may also have a ventilated shroud (or extractor hood) covering the disc. The tools attach through a hose to either a vacuum containing a HEPA filter or a central vacuum system located in the shop. Ensure the sandpaper the workers use is compatible with the sander; it should have the same number of holes as the sander and the holes should be properly aligned. Some sanders come with locking discs, while others have adhesive on the back of the sandpaper. Locking discs ensure proper alignment of the sandpaper with the holes. Measure the air velocity at the holes and multiply by the area of the holes. If the tool has a shroud, measure velocities at several places around the shroud and multiply by the area through which the air is drawn; add this value to the air flow through the holes. Sanders should have a minimum air flow of 10 cfm per inch of disc diameter; grinders should have a minimum air flow of 25 cfm per inch of disc diameter [37]. A portable HEPA vacuum will, in all likelihood, provide ventilation rates much lower than recommended; a central vacuum system, if properly operating, will probably provide better ventilation rates.

Filtration Systems

Filters are an integral part of the ventilation system. Check the system and determine the type of filters installed; HEPA filters are the best choice. Low to medium efficiency filters, such as the fabric pre-filters used in furnaces or HVAC systems, do not effectively capture the particulates generated during grinding and sanding [37]. To ensure proper operation of the ventilation system, filters should be routinely cleaned and/or changed. Filter cleaning and change-out can be effectively monitored by use of pressure drop gauges (such as magnehelic gauges) or by establishing a routine maintenance schedule based on hours of use. HEPA vacuums used with ventilated tools should have their collection bags frequently emptied.

PERSONAL PROTECTIVE EQUIPMENT AND ADMINISTRATIVE CONTROLS

Tables 6 and 7 summarize our recommendations for personal protective equipment during advanced composite material and fiberglass repair.

Respiratory Protection

Respirators are not required during clean wiping because of the brevity of the procedure. Respirators are also not required during core repair and lay-up because of the low volatility of the epoxy resins and amine hardeners. Our measurements indicate respiratory protection is only required during the process of depainting and sanding/grinding because of elevated chromate levels. However, our observation of advanced composite material repair indicate respiratory protection may be desired during scarfing. During some scarfing tasks, the ventilation system in use may not collect some residual dust. Additionally, during some scarfing and sanding/grinding tasks, the smell from low-temperature thermal decomposition products formed during grinding make workers uncomfortable [10]. We suspect an organic amine compound is creating this odor. A HEPA filter will provide collection of chromate particulates generated during depainting and sanding/grinding, and inhalable dusts/fibers generated during scarfing [38]. An organic vapor (OV) cartridge will remove the thermal decomposition odor. Therefore, an air-purifying respirator with a combination HEPA/OV cartridge will provide workers adequate respiratory protection.

Air-purifying respirators are classified as either powered or non-powered. Of the two, we recommend the use of powered air-purifying respirators (PAPRs) during depainting/scarfing and sanding/grinding. PAPRs consist of a cartridge, blower, and battery pack that mount on the worker's belt (see Figure 3). Air is provided to the worker through a breathing tube fitted to either a tight-fitting facepiece or a loose-fitting hood. A hooded PAPR has several benefits compared to a either a non-powered air-purifying respirator or a powered air-purifying respirator with a tight-fitting facepiece. Hooded PAPRs don't require either fit-testing or positive/negative seal (fit) checks before use, reducing workload for BEEs and training time for workers. Hoods provide a wider field of view and better peripheral vision. They allow civilians to wear beards and glasses, increasing their acceptance. Air flow into the hood provides cooling and makes it more comfortable to wear than tight-fitting facepieces in hot environments. There are no valves, straps, or rubber facepieces to inspect and wear out. Most hoods are disposable, reducing time needed to clean the respirator. A hooded PAPR with a HEPA/OV cartridge will provide adequate protection during most in-shop and flightline fiberglass repairs we would anticipate, allowing standardization at all Air Force composite repair and structural maintenance facilities.

Hand Protection

Disposable nitrile rubber gloves will provide adequate protection against particulates generated during depainting/scarfing and sanding/grinding, and solvents used during clean wiping. For core repair and lay-up procedures, though, a special type of glove is required. Many rubber gloves are made by a process called injection molding. The molds may be treated with a release agent, such as silicon, that allows the glove to be more easily removed from the mold. During lay-up procedures, if the release agent contacts either the resin system or the area where the resin system is to be applied, the laminate quality may be significantly reduced [39]. Additionally, any particulate within the glove, such as powder, will also reduce the quality of the composite patch as the powder has a tendency to contaminate the repair area. Comasec® manufactures a cotton-lined latex glove that does not contain any release agents (part number 1250-5) and can be used during both core repair and wet lay-up [40,41]. When the worker handles epoxy

Table 6. Minimum Recommended Controls and PPE for Advanced Composite Material Repair[a]

Operation	Engineering Controls	Personal Protective Equipment					
		Respiratory	Hand	Ear	Eye	Body	Foot
Depainting	Ventilated tool **or** moveable exhaust hood	Hooded PAPR w/ HEPA/OV cartridge	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Clean Wiping	General dilution ventilation	None	Disposable nitrile	None[d]	None	None	Safety toe boots
Scarfing	Ventilated tool **or** moveable exhaust hood	Hooded PAPR w/ HEPA/OV cartridge[e]	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Core Repair	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Wet Lay-Up	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Pre-Preg Lay-Up	General dilution ventilation	None	Cotton-lined latex	None[d]	None	None	Safety toe boots
Curing	General dilution ventilation	None	None	None	None	None	Safety toe boots

[a]Local Bioenvironmental Engineer may recommend more restrictive controls or PPE based on exposure monitoring

[b]When noise levels exceed 85 dBA

[c]Required only if no respirator is worn or half-facepiece respirator used

[d]Hearing protection may be required in locations where hazardous noise is produced from other sources

[e]Measured levels indicate respiratory protection not required, but may be desirable

Table 7. Minimum Recommended Controls and PPE for Fiberglass Repair[a]

Operation	Engineering Controls	Personal Protective Equipment					
		Respiratory	Hand	Ear	Eye	Body	Foot
Sanding/Grinding	Crossflow booth with ventilated tool	Hooded PAPR w/ HEPA/OV cartridge	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Clean Wiping	General dilution ventilation	None	Disposable nitrile	None[d]	None	None	Safety toe boots
Core Repair	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Wet Lay-Up	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Curing	General dilution ventilation	None	None	None	None	None	Safety toe boots

[a]Local Bioenvironmental Engineer may recommend more restrictive controls or PPE based on exposure monitoring

[b]When noise levels exceed 85 dBA

[c]Required only if no respirator is worn or half-facepiece respirator used

[d]Hearing protection may be required in locations where hazardous noise is produced from other sources

Figure 3. Powered Air-Purifying Respirator

resins and amine hardeners, such as during core repair and wet lay-up, we recommend a disposable nitrile rubber glove be worn underneath the Comasec glove to provide added protection.

Other Protective Equipment

Workers should wear cotton or tyvek® coveralls to reduce skin contact with the sanding dust. Disposable coveralls are preferred because they can be discarded after use; reusable cotton coveralls require laundering, which can lead to exposures to laundry personnel. Workers may require hearing protection during depainting and scarfing. Although we did not specifically measure the noise levels, the tools did generate a lot of noise. Workers must wear safety glasses if they don't wear a hooded or tight-fitting full-facepiece respirator during these operations. Safety toe boots must be worn during all composite repair procedures because of the potential for heavy aircraft parts and objects falling on the floor.

Workplace Practices

Control of Sanding Dust: It's important to contain all dusts within a designated portion of the composite repair facility, but especially chromate-containing dusts because of their carcinogenic potential. The main concern is transfer of dust into administrative areas, break rooms, and other areas where personnel not directly involved in the procedure may receive incidental exposures to chromates. It's especially important not to carry chromate containing dusts home to family members. The ideal set-up would include a controlled entrance/exit to the depainting/scarfing or sanding/grinding area, changing area, shower facility, and dressing area. Realizing the ideal seldom exists in the Air Force, as a minimum designate a dedicated entrance and exit to the sanding area. Workers should remove or HEPA vacuum their coveralls prior to exiting the depaint/scarfing or sanding/grinding area, whether that is a booth, a room, or designated area. Personnel not involved with the operations should not enter the area without proper protective equipment.

Dust Removal: Before clean wiping with a solvent, workers may remove dust generated during depaint/scarfing and sanding/grinding activities with compressed air. Removal of dust with compressed air increases the potential for worker exposures from dust resuspension. HEPA vacuums remove dusts as effectively and with less exposure to personnel than compressed air. Also, workers should avoid dry sweeping to clean-up work areas; use HEPA vacuums to clean-up residual dust.

Venting of Curing Procedure: Composite parts may be cured in an oven or autoclave. Vent this equipment to the exterior of the building whenever possible to prevent worker exposures to curing vapors. If workers use the vacuum bagging technique, vent the central vacuum system to the exterior of the building, if possible.

Limit Personnel Exposed: When depainting/scarfing or sanding/grinding, only one worker should mechanically abrade the aircraft part at a time. If several composite repair operations are occurring in the composite repair facility, position the parts so dust generated by one operation does not pass into another worker's breathing zone.

AIRCRAFT BATTLE DAMAGE REPAIR (ABDR)

Disclaimer

This document addresses ABDR in peacetime and uncontaminated wartime environments, and during NBC training. It does not address ABDR in NBC environments; refer to AF Handbook 32-4014, Volume 4 for protective equipment requirements in this situation [42].

Process Description

Aircraft battle damage is most frequently caused by projectiles and usually results in holes surrounded by jagged edges, cracks, and tears. Removal of the damage is accomplished by drilling, grinding, or cutting away the damaged material [43]. ABDR operations encompass all structural and system repairs necessary to repair this damage and restore the aircraft to flying status. ABDR is governed by Technical Order 1-1H-39, *Aircraft Battle Damage Repair*, and by weapon system specific 39 series technical orders. The AFTO Form 97, *Aerospace Vehicle Battle Damage Repair Debrief/Assessment Record* is used to record repairs accomplished on aircraft [43]. Combat Logistics Support Squadron (CLSS) and Air Force Special Operations Command (AFSOC) personnel perform ABDR operations at fixed air bases or in remote locations where aircraft have been damaged.

During ABDR operations workers may perform composite repair on aircraft parts remaining on the aircraft. Damage to composite structures will often consist of a splintered hole surrounded by delamination and ply peeling (see Figure 4). Mechanically fastened aluminum or stainless steel patches may be used to repair composite material damage [43], or the composite material damage may be repaired using the sequential procedures described in either this technical report or aircraft manufacturers' literature [44]. ABDR composite material maintenance operations will also vary somewhat across the Air Force depending on the aircraft under repair. CLSS and AFSOC squadrons maintain mobile trailers for ABDR training equipment and supplies. Many of these trailers are pre-positioned throughout Europe and the Far East in the event of a wartime contingency. When needed, the trailer is brought to the site or the base where the aircraft repairs are needed. There is a limited amount of supply and equipment storage space within the ABDR trailers [45].

ABDR operations will usually take place in environments without NBC contamination. In uncontaminated environments, workers should wear the same personal protective equipment as during in-shop composite material repairs [45]. ABDR operations, however, may take place in areas under the threat of NBC contamination. To prepare for contingencies involving NBC contamination, workers practice ABDR operations using the ground crew ensemble and the MCU-2A/P protective mask (see Figures 5 and 6). Workers may train for ABDR operations in environments both with and without NBC contamination during base-wide or local exercises.

Air Sampling and Data Evaluation

Air sampling requirements and data interpretation for ABDR operations are described in the previous sections of this technical report.

Figure 4. Projectile Damage on F-16 Flight Control Surface

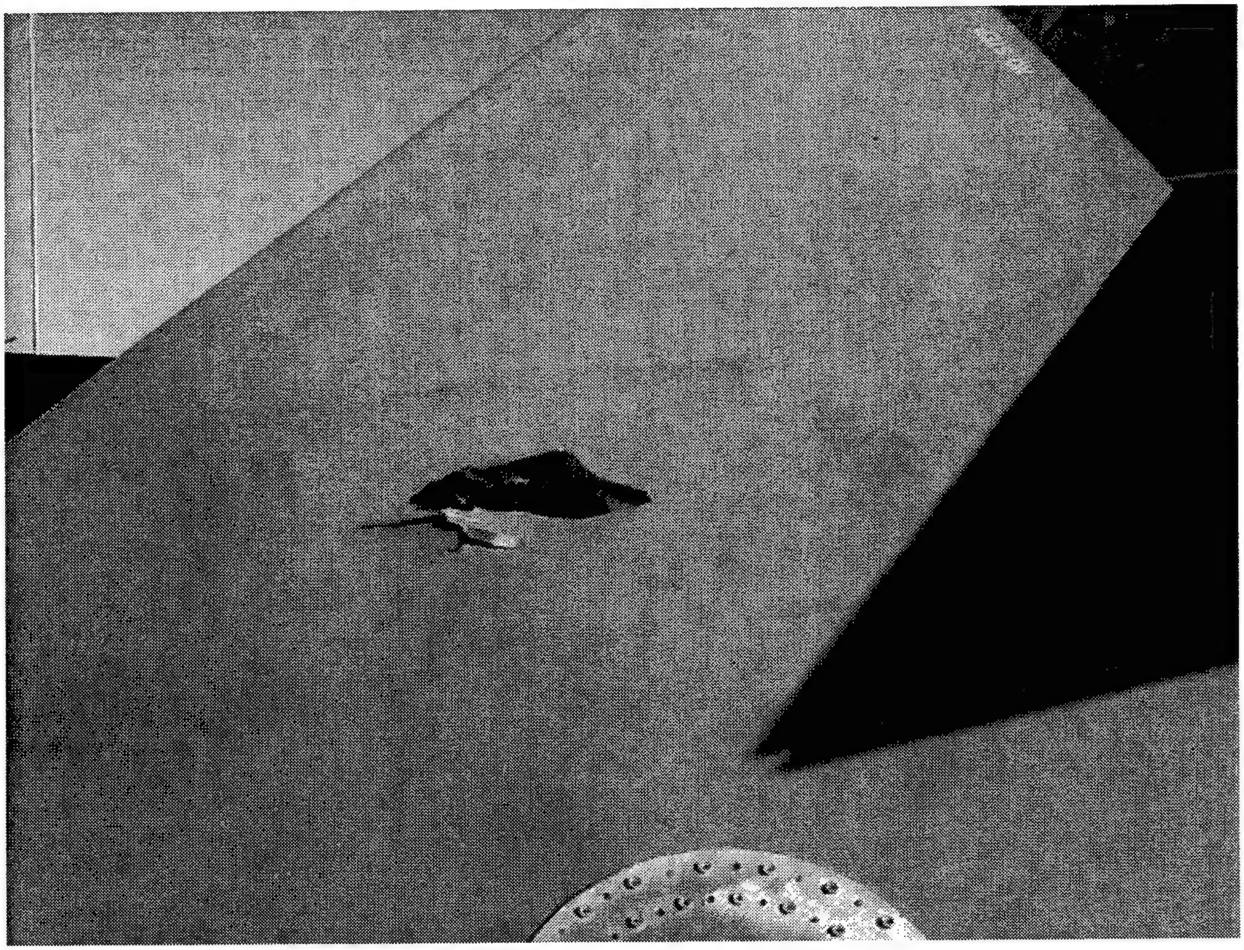


Figure 5. Aircraft Battle Damage Repair of Graphite/Epoxy Composite (View 1)

CA

Figure 6. Aircraft Battle Damage Repair of Graphite/Epoxy Composite (View 2)

Ventilation Systems: In-shop composite material repairs generally are accomplished with some form of ventilation. Ventilation systems used in-shop include crossflow sanding booths, hand-held vacuum hoses, downdraft tables, moveable exhaust hoods with flexible ducting, and ventilated pneumatic tools (also referred to as low volume-high velocity exhaust systems). The primary purpose of the ventilation system is to collect particulates generated during depainting, scarfing, sanding, and grinding operations [37]. For on-aircraft repairs such as those accomplished during ABDR, ventilated tools are the most appropriate system. Most ventilated tools are pneumatically driven and require a compressed air source to operate. The HEPA vacuum units, an integral part of ventilated tool systems, take up a minimum of twelve cubic feet of storage space. Compressed air sources may be limited during contingencies, and ABDR storage trailers may lack the space to store HEPA vacuum units, limiting the utility of ventilated tools [45].

Evaluation of Ventilated Pneumatic Tools: Ventilated sanders and grinders typically have a number of holes located in the rotary disc through which particulates are drawn. The tool may also have a ventilated shroud (or extractor hood) covering the disc. The tools attach through a hose to a vacuum containing a high-efficiency particulate air (HEPA) filter. Ensure the sandpaper the workers use is compatible with the sander; the sandpaper should have the same number of holes as the sander and the holes should be properly aligned. Some sanders come with locking discs, while others have adhesive on the back of the sandpaper. Locking discs ensure proper alignment of the sandpaper with the holes. Measure the air velocity at the holes and multiply by the area of the holes. If the tool has a shroud, measure velocities at several places around the shroud and multiply by the area through which the air is drawn; add this value to the air flow through the holes. Sanders should have a minimum air flow of 10 cfm per inch of disc diameter; grinders should have a minimum air flow of 25 cfm per inch of disc diameter [37]. A portable HEPA vacuum will, in all likelihood, provide ventilation rates much lower than recommended, but still remove large amount of particulates.

Respiratory Protection: Table 8 shows our recommended respiratory protection for work areas without NBC contamination. For operations where respiratory protection is required, an air-purifying respirator with a combination organic vapor (OV)/HEPA cartridge will provide workers adequate respiratory protection [38]. Air-purifying respirators are classified as either powered or non-powered. Of the two, we recommend the use of powered air-purifying respirators (PAPRs) during depainting, scarfing, sanding, and grinding. PAPRs consist of a cartridge, blower, and battery pack that mount on the worker's belt (see Figure 3). Air is provided to the worker through a breathing tube fitted to either a tight-fitting facepiece or a loose-fitting hood. A hooded PAPR has several benefits compared to a either a non-powered air-purifying respirator or a powered air-purifying respirator with a tight-fitting facepiece. Hooded PAPRs don't require either fit-testing or positive/negative seal (fit) checks before use, reducing workload for BEEs and training time for workers. Hoods provide a wider field of view and better peripheral vision. They allow civilians to wear beards and glasses, increasing their acceptance. Air flow into the hood provides cooling and makes it more comfortable to wear than tight-fitting facepieces in hot environments. There are no valves, straps, or rubber facepieces to inspect and wear out. Most hoods are disposable, reducing time needed to clean the respirator. A hooded PAPR with a HEPA/OV cartridge will provide adequate protection during ABDR operations, allowing standardization of all Air Force ABDR activities.

Hand Protection: Table 8 shows hand protection recommended for use in work areas without NBC contamination. Disposable nitrile rubber gloves will provide adequate protection against particulates generated during depainting/scarfing and sanding/grinding, and solvents used during clean wiping. For core repair and lay-up procedures, though, a special type of glove is required. Many rubber gloves are made by a process called injection molding. The molds may be treated with a release agent, such as

Table 8. Minimum Recommended Controls and PPE for ABDR Composite Repair[a]
(Uncontaminated Environments)

Operation	Engineering Controls	Personal Protective Equipment					
		Respiratory	Hand	Ear	Eye	Body	Foot
Depainting	HEPA ventilated tool	Hooded PAPR w/ HEPA/OV cartridge	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Sanding/Grinding	HEPA ventilated tool	Hooded PAPR w/ HEPA/OV cartridge	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Clean Wiping	General dilution ventilation	None	Disposable nitrile	None[d]	None	None	Safety toe boots
Scarfing	HEPA ventilated tool	Hooded PAPR w/ HEPA/OV cartridge[e]	Disposable nitrile	Plugs or muffs[b]	Safety glasses[c]	Tyvek or cotton coveralls	Safety toe boots
Core Repair	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Wet Lay-Up	General dilution ventilation	None	Disposable nitrile beneath cotton-lined latex	None[d]	None	None	Safety toe boots
Pre-Preg Lay-Up	General dilution ventilation	None	Cotton-lined latex	None[d]	None	None	Safety toe boots
Curing	General dilution ventilation	None	None	None	None	None	Safety toe boots

[a]Local Bioenvironmental Engineer may recommend more restrictive controls or PPE based on exposure monitoring
[b]When noise levels exceed 85 dBA
[c]Required only if no respirator is worn or half-facepiece respirator used
[d]Hearing protection may be required in locations where hazardous noise is produced from other sources
[e]Measured levels indicate respiratory protection not required, but may be desirable

silicon, that allows the glove to be more easily removed from the mold. During lay-up procedures, if the release agent contacts either the resin system or the area where the resin system is to be applied, the laminate quality may be significantly reduced [39]. Additionally, any particulate within the glove, such as powder, will also reduce the quality of the composite patch. Comasec® manufactures a cotton-lined latex glove that does not contain any release agents (part number 1250-5) and can be used during both core repair and lay-up [40,41]. If the worker handles epoxy resins and amine hardeners, such as during core repair and wet lay-up, we recommend a disposable nitrile rubber glove be worn underneath the Comasec glove to provide added protection.

Other Protective Equipment: Table 8 summarizes other protective equipment that should be worn in uncontaminated work areas. Workers should wear cotton or tyvek® coveralls to reduce skin contact with the sanding dust. Disposable coveralls are preferred because they can be discarded after use; reusable cotton coveralls require laundering, which can lead to exposures to laundry personnel. Workers may also need to wear hearing protection during pneumatic tool use. Workers should wear safety glasses if they don't wear a respirator during these operations, or if they use a half-facepiece respirator that doesn't provide eye protection. Safety toe boots should be worn during all composite repair procedures due to the potential for falling tools.

Work Area Practices: Workers may remove dust generated during ABDR operations with compressed air. Removal of dust with compressed air increases the potential for worker exposures from dust resuspension. HEPA vacuums remove dusts as effectively and with less exposure to personnel than compressed air. When depainting/scarfing or sanding/grinding, ideally only one worker should mechanically abrade the aircraft part at a time to prevent dust from entering the breathing zone of other workers. However, repair priorities may demand concurrent operations.

ABDR in NBC Training Scenarios

Ventilation Systems: Although ventilated tools have been shown to reduce worker exposures to contaminants during composite repair (see Appendix A), they are not appropriate for use in NBC environments. If the vacuum mechanism of ventilated tools becomes contaminated with radioactive particulates or chemical/ biological agents, it would be virtually impossible to decontaminate.

Respiratory Protection: Table 9 shows our recommended respiratory protection for ABDR in NBC training scenarios. For operations completed in an NBC training scenario, the MCU-2A/P protective mask with a serviceable C-2 canister protects the respiratory tract from chemical and biological warfare agents and radioactive particulates [42]. The protection factor of a respirator is the minimum expected workplace level of respiratory protection that a properly functioning respirator provides. Respirator protection factor studies accomplished by the Army, using a chamber and corn-oil testing procedure, show that ninety-five percent of individuals wearing the MCU-2A/P mask have quantitative fit factors greater than 1667 [46]. The hazard ratio is the measured exposure level divided by the occupational exposure limit. The maximum hazard ratio found during ABDR was 20 for chromates (see Appendix C), much less than the fit factor of 1667. Therefore, the large majority of ABDR workers will have a sufficiently high fit factor with the MCU-2A/P mask to provide adequate protection.

Respirator Canister: The C-2 canister contains a high-efficiency particulate air (HEPA) filter and impregnated charcoal. If an aerosol contaminant has a mass median aerodynamic diameter greater than two microns, any filter, whether a dust, mist, fume or HEPA, will provide adequate protection to the wearer [47]. A HEPA filter is the most protective, providing a 99.97% filtration efficiency at a particle size of 0.3 micron [38]. IH Branch field studies show the mass median diameter of sanding particulates to be greater than 16 microns [48]. Therefore, the HEPA filter in the C-2 canister will collect particulates

Table 9. Minimum Recommended Controls and PPE for ABDR Composite Repair
(NBC Training Scenarios)

Operation	Engineering Controls	Personal Protective Equipment					
		Respiratory	Hand	Ear	Eye	Body	Foot
Depainting	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	Ear plugs[a]	None[b]	Ground crew ensemble	Combat boots w/ overshoe
Sanding/Grinding	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	Ear plugs[a]	None[b]	Ground crew ensemble	Combat boots w/ overshoe
Clean Wiping	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	None[c]	None	Ground crew ensemble	Combat boots w/ overshoe
Scarfing	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	Ear plugs[a]	None[b]	Ground crew ensemble	Combat boots w/ overshoe
Core Repair	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	None[c]	None	Ground crew ensemble	Combat boots w/ overshoe
Wet Lay-Up	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	None[c]	None	Ground crew ensemble	Combat boots w/ overshoe
Pre-Preg Lay-Up	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	None[c]	None	Ground crew ensemble	Combat boots w/ overshoe
Curing	None	MCU-2A/P mask w/hood	Chemical protective glove (butyl rubber)	None	None	Ground crew ensemble	Combat boots w/ overshoe

[a]When noise levels exceed 85 dBA
[b]Not required as MCU-2/P provides adequate eye protection
[c]Hearing protection may be required in locations where hazardous noise is produced from other sources

generated during ABDR sanding/grinding and depainting/scarfing. The impregnated charcoal will provide limited protection from a wide variety of industrial chemical vapors, including isopropyl alcohol and methyl ethyl ketone, the predominant solvents used in ABDR [49,50]. Industrial solvent exposures will be very low during ABDR composite repair, as they are during in-shop composite repair, because of the brevity of the operation. Therefore, the charcoal in the C-2 canister will provide sufficient protection against solvents used in ABDR clean wiping.

Canister Change-Out: During training, personnel should change the C-2 canister whenever there is an increase in breathing resistance. An increase in breathing resistance is caused by excessive particulate loading of the filter. As the filter is loaded, and breathing resistance increases, there is a greater potential for the face-to-facepiece seal to break and leakage to occur. The C-2 canister should be changed within thirty days of exposure to industrial chemicals [51]. Personnel should also change the canister when physical damage occurs or the filter becomes wet.

Hand Protection: The butyl rubber protective gloves worn as part of the ground crew ensemble [42] provide adequate protection against the particulates and chemicals encountered during composite repair operations [52,53].

Other Protective Equipment: Table 9 summarizes protective equipment for use during NBC training scenarios. The ground crew ensemble reduces skin contact with sanding dust and provides protection to personnel from particulates and chemicals encountered during ABDR. The ground crew ensemble should be HEPA vacuumed after training use to remove particulates. The ground crew ensemble should also be washed or dry cleaned after training use to remove any particulates remaining on the garment. Workers may need to wear hearing protection during pneumatic tool use. The MCU-2A/P mask provides adequate eye protection for the ABDR operations. Safety toe boots should be worn beneath the ground crew ensemble footwear covers.

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APPENDIX A: ADVANCED COMPOSITE MATERIAL REPAIR FIELD STUDY RESULTS

Survey Locations

A major part of our evaluations involved determining the effectiveness of various ventilation systems to control exposures during advanced composite repair operations. Field studies were done at Charleston, Robins, Hill AFBs, and the Structural Maintenance School at Pensacola Naval Air Station; the Advanced Composite Support Office suggested these locations based on the various types of ventilation systems in use. In addition, the Advanced Composite Support Office set-up a field experiment at McClellan AFB to perform controlled comparisons between different ventilation systems.

Field Studies

Systems Evaluated: The following ventilation systems were in use during scarfing at the field sites: moveable exhaust hoods with flexible ducting, hand-held vacuum hoses, and crossflow sanding booths.

Results: Worker exposures to respirable dust and fibers during scarfing, using the three different ventilation systems, are summarized in Tables A-1 and A-2. Means were determined from Land's procedure for calculating exact confidence intervals around the mean of lognormally distributed data [54]. Overall exposures were lowest with the moveable hood.

Table A-1. Respirable Dust Exposures During Scarfing (Task Exposures, mg/m^3)

Ventilation System	Sample Number	Range	Mean
Moveable exhaust hood	10	0.053 - 0.777	0.295
Hand-held vacuum hose	3	0.717 - 11.78	4.642
Crossflow booth	2	0.847 - 0.964	0.906

Table A-2. Fiber Exposures During Scarfing (Task Exposures, f/cc)

Ventilation	Sample Number	Range	Mean
Moveable exhaust hood	9	0.001 - 0.030	0.018
Hand-held vacuum hose	3	0.026 - 0.153	0.074
Crossflow booth	2	0.004 – 0.184	0.094

Discussion: Each ventilation system had certain disadvantages that should be considered when evaluating them. The moveable exhaust hood visually appeared to collect dust better than the other two systems, but had to be positioned within a few inches of the work surface to effectively remove particulates. Workers had to hold the vacuum hose with one hand while grinding with the other. This positioning results in the workers' breathing zones being physically closer to the point of contaminant generation, increasing exposures. The crossflow booth offers a large space for personnel to work in. Unfortunately, the workers tended to position themselves so dust generated from other composite operations taking place in the booth passed through their work areas and breathing zones before being

exhausted. This positioning probably resulted in greater worker exposures than if only one worker was scarfing in the booth. In addition to these three systems, we also observed scarfing procedures on a downdraft table (sampling data not available). The system visually did not appear to very effective at controlling particulates, but this may have been because the filters needed cleaning, which may have reduced the available airflow.

Conclusions: Our field studies indicate that among the systems tested, a moveable exhaust hood with flexible ducting provided the best control of contaminants generated during in-shop advanced composite material repair operations.

McClellan AFB Field Experiment

Systems Evaluated: An experienced Structural Maintenance technician performed advanced composite material depainting and scarfing tasks. Having only one worker accomplish the tasks reduced between-worker variability. The tasks were accomplished at the same composite repair facility and on the same work bench.

Depainting: Two aircraft part depainting tasks were monitored. The worker first sanded using an unventilated pneumatic dual action rotary sander, then sanded with a ventilated pneumatic dual action rotary sander. Breathing zone air samples for inhalable dust, respirable dust, and hexavalent chromium were collected during the depainting tasks. The results are shown in Table A-3. During both tasks and for all contaminants measured, task exposures were less when using the ventilated sander.

Table A-3. Comparison of Task Exposures During Depainting (mg/m^3)

Depaint Tool	Inhalable Dust		Respirable Dust		Hexavalent Chromium	
	Task 1	Task 2	Task 1	Task 2	Task 1	Task 2
Unventilated Sander	15.59	11.60	4.56	8.78	0.059	0.046
Ventilated Sander	4.34	0.049	1.84	1.03	0.008	0.013

Scarfing: The worker scarfed six-inch diameter patches on three types of composite material. Scarfing took place in a crossdraft sanding booth. The worker used three combinations of commonly encountered work tools and ventilation systems: an unventilated right angle grinder; a ventilated right angle grinder; and a right angle grinder in combination with a vacuum hose held by the worker. Each of the three combinations were monitored with the crossdraft both on and off, for a total of six different variations. Air samples for inhalable dust, respirable dust, and fibers were collected. The results are shown in Table A-4. In one case, no weight change was noted on the filter and the result is indicated as "ND." Some of the fiber results are reported as "OL" or overloaded. The lowest task exposures found are indicated by boldface type. Overall, task exposures were lowest when using the ventilated grinder as compared to using the crossdraft booth by itself or the hand-held vacuum hose.

Discussion: The depainting results clearly show that the ventilated sander reduced worker exposures. Although not enough samples were taken during the scarfing procedures to make a valid statistical comparison, the data indicates that all the ventilation systems tested reduced worker exposures. Of the three ventilation systems tested, the results suggest that the ventilated grinder reduced exposures the most,

Table A-4. Comparison of Task Exposures During Scarfing

Ventilation System	Inhalable Dust (mg/m^3)			Respirable Dust (mg/m^3)			Fibers (f/cc)		
	Gra/Kev	Graphite	Fiberglass	Gra/Kev	Graphite	Fiberglass	Gra/Kev	Graphite	Fiberglass
None	8.350	27.429	9.378	9.977	0.419	1.313	OL[2]	OL[2]	OL[2]
Crossdraft booth	3.569	4.607	3.95	1.992	0.389	3.5	0.0475	OL[2]	0.0079
Hand-held vacuum hose	5.708	16.684	2.491	2.623	3.261	2.016	0.0736	OL[2]	0.004
Vacuum hose w/ crossdraft booth	2.265	8.045	ND[1]	**0.226**	**0.311**	1.216	0.1206	0.143	0.0158
Ventilated grinder	**0.677**	**0.83**	1.351	0.734	0.801	4.032	0.0241	0.0998	0.0041
Ventilated grinder w/ crossdraft booth	0.779	8.97	**0.59**	0.649	1.489	**0.465**	**0.0041**	**0.0079**	**0.0039**

[1]None detected

[2]Filter overloaded

although additional sampling results are needed to confirm this. Two of the respirable dust results were lower for the vacuum hose than for the ventilated grinder. This may be explained in part by worker positioning. When holding the vacuum hose, the worker moved around a lot because of fatigue. This movement shifted his position in relation to the work surface and also shifted the location of the cyclone sampler attached to his coveralls. The worker's frequent repositioning may also have shifted the orientation of the cyclone aerosol inlet, resulting in the lower readings found.

Conclusions: Ventilated sanders effectively reduce worker exposures during depainting procedures. Ventilated grinders and hand-held vacuum hoses were more effective than crossdraft booths during scarfing procedures, probably because they capture contaminants at the point of generation.

APPENDIX B: FIBERGLASS FIELD STUDY RESULTS

Survey Locations

We visited several bases during the field studies. The bases included Robins, Hurlburt, Eglin, Hill, and McClellan AFBs, and the Cherry Point Naval Aviation Depot. The Advanced Composites Support Office suggested these locations based on the various types of ventilation systems and personal protective equipment in use.

Results

Results of the field work are summarized in Tables B-1 and B-2. Table B-1 shows fiberglass task exposure data while Table B-2 indicates 8-hr TWA exposures. Means and 95% confidence limits were determined from Land's procedure for calculating exact confidence intervals around the mean of lognormally distributed data [54]. At bases where the workers used no ventilation during fiberglass repair, we observed large amounts of sanding dust on the floors, tables, and the workers.

Table B-1. Exposures During Sanding/Grinding (Task Exposures)

Substance	Sample Number	Range	Mean	95% Confidence Limits
Inhalable Particulate[1]	24	0.083 - 26.31	3.837	(2.497, 8.363)
Fibers[2]	16	0.011 - 0.309	0.073	(0.049, 0.156)

Table B-2. Exposures During Sanding/Grinding (8-hr TWA Exposures)

Substance	Sample Number	Range	Mean	95% Confidence Limits
Inhalable Particulate[1]	24	0.017 - 2.476	0.362	(0.229, 0.857)
Fibers[2]	16	0.001 - 0.013	0.006	(0.004, 0.012)

[1]Units mg/m^3
[2]Units f/cc

APPENDIX C: ABDR FIELD STUDY RESULTS

Field studies during ABDR operations were accomplished at McClellan, Tinker, and Hill AFBs. Monitored ABDR operations are considered representative of ABDR composite repair operations performed throughout the Air Force. Table C-1 shows the sampling results from the ABDR field studies. Task exposures were below the Air Force 8-hr occupational exposure limit (OEL) for fibers and particulates [13]. Task exposures during ABDR were generally higher than those found during in-shop advanced composite material repairs, probably because ventilation systems were not in use.

Table C-1. Worker Task Exposures During Aircraft Battle Damage Repair

Base	Operation	Worker	Task Time (min)	Particulates (mg/m^3)			Fibers (f/cc)
				Inhalable	Respirable	Chromium VI	
Tinker	Depainting/scarfing F-16 stabilizer	Worker #1 Worker #2	53 44	4.545 5.962	2.375 2.776	0.00157 0.00066	0.0502 0.0248
	Depainting/scarfing F-16 stabilizer	Worker #1 Worker #2	29 29	2.136 3.489	2.796 2.025	0.00100 0.00139	0.0044 0.0333
	Depainting/scarfing F-16 stabilizer with weather enclosure	Worker #1 Worker #2	47 47	8.167 6.974	3.191 2.088	0.00249 0.00177	0.0051 0.0027
McClellan	Scarfing simulated aircraft section	Worker #3	60	1.953	< 0.20	--	0.0019
	Scarfing simulated aircraft section	Worker #3	60	2.371	0.532	--	0.0007
Hill	Depainting/scarfing F-16 stabilizer	Worker #4 Worker #5	38 38	6.554 0.234	< 0.48 < 0.55	0.00973 0.00266	0.0221 0.0563